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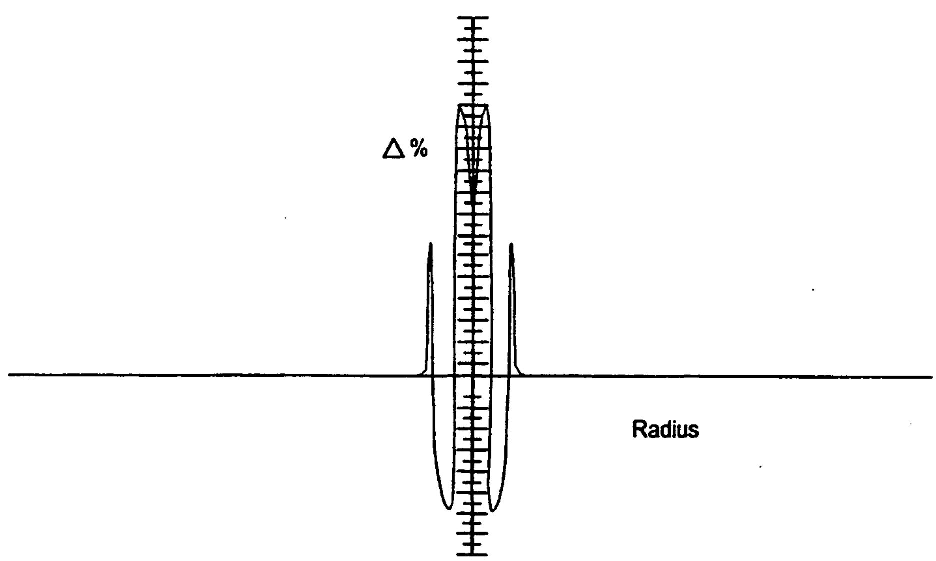

(57) Abstract

An optical fiber and method of making, wherein the optical fiber alternates between regions having different diameters along its length, wherein the refractive index of said blank and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion at a wavelength which is greater than 1480 nm, yet preferably has a low net dispersion and dispersion slope. A preferred such profile consists of a core region surrounded by a cladding region, said core region comprised of a central core region which is updoped with respect to said cladding region, said central core region surrounded by a moat region which is downdoped with respect to said cladding region, and said moat region is surrounded by an annular ring region which is updoped with respect to said cladding region.

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METHOD OF MAKING OPTICAL FIBERS

Field of the Invention

The invention is directed to a method for making an optical fiber having optical properties that systematically vary along its length. This method is particularly useful for making dispersion managed (DM) single-mode optical waveguide fibers.

Technical Background

The recent advent of wavelength division multiplexing and amplifiers has increased system requirements to lower the dispersion and dispersion slope of the optical fiber. Several unique methods of making dispersion managed fiber have previously been disclosed that address these properties nicely. See, for example, U.S. patent application Serail No. 08/844,997 (Berkey et al.) filed April 23, 1997, and U.S. Patent Application Serial No. 08/584,868, filed January 11, 1996, the specifications of which are all hereby incorporated by reference.

Many of the methods to date have been relatively complex and therefore may involve higher cost than more standard methods of manufacture because of this complexity. It would be desirable to develop an alternative, easier method to manufacture optical fiber whose dispersion characteristics vary between positive and negative along the longitudinal direction of the optical fiber, particularly in the 1550 nm operating window.

Summary and Description of the invention

One aspect of the present invention relates to an optical fiber having different diameters along its length, and a method of making such fiber. The index of refraction profile of the optical fiber preform is selected so that, when the optical fiber preform is drawn into an optical fiber having such differing diameters along its length, the result is an optical fiber which varies along its longitudinal length (i.e., corresponding to the regions of differing diameters) between regions of negative and positive dispersion in the 1550 nm operating window, which preferably consists of the window between about 1480 and about 1625 nm. In preferred embodiments, the fiber also varies between regions of negative and positive dispersion slope along the length of the fiber in the 1550 nm operating window. Preferably, the regions of negative dispersion correspond to regions of negative dispersion slope and the regions of positive dispersion correspond to regions of positive dispersion slope. By different diameters, it is meant that the difference in diameters between these alternating sections is sufficient to result in noticeably different dispersion properties along the length of the fiber. For example, in a preferred embodiment, the alternating segments have diameters which differ in magnitude by more than three (3), and more preferably more than five (5) microns.

Not just any refractive index profile can be employed to produce a fiber having such varying negative and positive dispersion characteristics along its length. For example, standard single mode fiber changes dispersion very little with diameter, particularly at 1550 nm. One preferred family of refractive index profiles which enables a fiber having the desired alternating dispersion characteristics, when drawn to differing diameters along its length, consists of a core region surrounded by a cladding region, wherein the core region comprises a central core region which is updoped with respect to said cladding region, said central core region surrounded by a moat region which is downdoped with respect to said cladding region, and said moat region is surrounded by an annular ring region which is updoped with respect to said cladding region. Preferred radius and delta percent values for such profiles will be discussed further below.

The result is a fiber which can be made to vary along its length between regions of negative and positive dispersion and between negative and positive dispersion slope, yet has a net dispersion and dispersion slope which are both relatively low. Preferred fibers made in accordance in the present invention yield a net dispersion of less than 1.0 ps/nm-km at 1550 nm and a dispersion slope of less than .03 ps/nm^2-km over the wavelength range 1480 to 1625 nm, more preferably a dispersion of .5 ps/nm-km and a dispersion slope of less than .01 ps/nm^2-km over the wavelength range 1480 to 1625 nm, and the most preferable fibers made in accordance with the present invention exhibit a dispersion of less than .1 ps/nm-km at 1550 nm and a dispersion slope of less than .005 ps/nm^2-km over the wavelength range 1480 to 1625 nm.

Modern feedback control loops can be used to control both downfeed rate and draw rate to control fiber diameters. The fiber O.D. change is most quickly achieved by changing the tractor (fiber take-up) speed and thus the draw rate. As a result, the diameter of the core of the fiber changes as the tractor speed changes, thereby enabling the transition region between different diameters to be kept relatively short. In preferred embodiments, the fiber is drawn so that the segments of different diameters differ in magnitude of outside fiber diameter by greater than 3 microns, more preferably greater than 5 microns, and most preferably greater than 10 microns measured at the outside diameter of the fiber. Also, the fiber is preferably alternates between sections which are between 100 m and 3 km in length, and more preferably the alternating sections are least 250 m in length and less than 2 km

Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are

incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Brief Description of the Drawings

Fig. 1 illustrates a first profile for use in making an optical fibers whose dispersion characteristics vary between negative and positive along its length in accordance with the present invention.

Fig. 2 illustrates a second index of refraction profile which can be used to make a fiber having varying dispersion characteristics along its length in accordance with the present invention.

Detailed Description of the Preferred Embodiments

In a preferred embodiment of the invention, a glass optical fiber preform is manufactured which has an index of refraction profile sufficient so that, when the fiber is drawn into an optical fiber having the different diameters along its length, the result is an optical fiber which also varies along its longitudinal length (i.e., corresponding to the regions of differing diameters) between regions of negative and positive dispersion and also between regions of negative and positive dispersion slope in the 1550 nm operating window, which preferably consists of the window between 1480 and 1625 nm.

Such a core refractive index profile is illustrated in Figs. 1 and 2. In Figs. 1 and 2, the index of refraction of the cladding corresponds to zero on the Y-axis. Both of the profiles illiustrated in Figs. 1 and 2 exhibit an updoped centerline core region which is surrounded by a moat and updoped annular ring. The moat between the centerline region and the annular ring preferably is downdoped with respect to the cladding.

The profiles of the type illustrated in Figs. 1 and 2 comprise a central core region having a delta percent, relative to the cladding (wherein delta = $(n_1^2 - n_2^2)/2n_1^2$), between about +.5 to 1.5 and a depressed moat core region which surrounds the central core region. The depressed moat preferably is in the range of -.15 delta percent or lower (preferably no lower than -.7 delta percent) relative to the cladding, wherein delta = $(n_1^2 - n_2^2)/2n_1^2$. An optional updoped annular ring may also be employed. In some preferred embodiments

wherein the updoped annular ring is employed, the annular ring exhibits a delta percent which is between +.10 and +.8. In the embodiment illustrated in Fig. 1, the central core has a delta percent of about +.85, a depressed moat of -.4 delta percent, and an annular ring surrounding the depressed moat which has a delta percent of about 4.1 percent.

The radii of the three segments (measured to the extrapolated intersection with the x-axis, the x-axis being equal to the index of refraction of the cladding layer) is preferably selected so that, if the radius of the first centerline up-doped segment is taken to be a, the radius of the moat section taken to be b, then b/a preferably is between about 1.5 to 3.0, more preferably between about 2 and 2.5. If the outer radius of the optional annular ring is c, then c/a is preferably between about 2.5 and 3.0.

The profiles disclosed in Figs. 1 and 2 meet these radius limitations and also comprise a central core region having a delta percent between about +.7 to 1.0, a depressed moat core region in the range of -.25 to -.5 percent delta, and an annular ring surrounding the depressed moat in the range of about +.2 to +.8 percent.

Such refractive index profiles can be made using any of the techniques known in the art, and preferably are made using a chemical vapor deposition technique such as the outside vapor deposition (OVD) process, the vapor axial deposition (VAD) process, or the inside vapor (MCVD) deposition process. The preferred manufacturing technique is via OVD. Conventional dopant materials can be used for the doping of the silica, e.g., germania can be used for updoping and fluorine can be used for downdoping.

After a preform is made having the desired core refractive index profile, a fiber is drawn from the preform which has a different diameter along its length. By different, it is meant that the difference in diameters between these alternating sections is sufficient to result in noticeably different properties along the length of the fiber. For example the different diameters may be separated by a difference of more than three (3), more preferably more than five (5) microns.

The core profile illustrated in Fig. 1 has dispersion properties that are very sensitive to core diameter. Normally this is considered a bad attribute as

fiber manufacturers would normally prefer a wide core diameter tolerance in order to facilitate control of the manufacturing process to produce higher yields. Yet, we have found that, by employing the methods of the present invention, the sensitivity of the profile shown in Fig. 1 can be used advantageously to achieve dispersion management by simply drawing the preform blank to different outside fiber diameters.

Set forth below in Table 1 are the dispersion properties at 1550 nm for a fiber drawn, in accordance with the invention, from an optical fiber preform having the refractive index illustrated in Fig. 1. The Fig. 1 profile is remarkable for its symmetry of substantially matching both the dispersion and dispersion slopes when the core is drawn at different diameters. As can be seen in Table I, by drawing the optional fiber preform having the index of refraction illustrated in Fig. 1 into a fiber whose outside diameters alternated between 115 and 133.5 microns, one can achieve near zero net dispersion with very low slope over the length of the fibers.

Table I

Fiber O.D.	Dat 1550	Slope	Zero Dispersion Wavelength
115	-7.08	-.03	1315
125	+1.87	+.001	
135	+9.3	+.025	1179

Table II shows the dispersion properties for a 14 km section of fiber alternately drawn as described above, i.e., into a fiber whose outside diameter alternated between 115 and 133.5 microns (i.e., a difference in diameter between alternating adjacent sections which is greater than 10 microns) every 500 meters. Of course the segment lengths need not be of equal length to best compensate the dispersion of various profiles, and instead these lengths can be varied according to the dispsersion characteristics of the .Because the fiber is drawn to have varying outside diameters, the physical core of the fiber will also likewise have varying diameters. The net total dispersion of the resultant fiber is -.17 ps/nm-km at 1550 with a slope of about -.00158 ps/nm^2-km over the wavelength range 1480 to 1625 nm. Also important is the fact that the zero

dispersion wavelength is in all cases outside the 1500 to 1700 nm range. The fiber illustrated with reference to Table II also exhibited a mode field diameter of about 25.5 microns, and a zero dispersion wavelength of about 1440.68.

Table II

Wavelength (nm)	Total Dispersion -14km
1500	-0.09362
1505	-0.10151
1510	-0.10941
1515	-0.11730
1520	-0.12519
1525	-0.13308
1530	-0.14097
1535	-0.14886
1540	-0.15675
1545	-0.16465
1550	-0.17254
1555	-0.18043
1560	-0.18832
1565	-0.19621
1570	-0.20410
1575	-0.21199
1580	-0.21988
1585	-0.22778
1590	-0.23567
1595	-0.24356
1600	-0.25145

Although the disadvantage to fibers produced in this manner is that the fiber is not a uniform 125 micron OD, the advantage is that it can be offered at a significantly lower cost than other unitary dispersion managed fibers because of the simplicity of the manufacturing technique employed to make it.

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A method of making an optical fiber comprising drawing a optical fiber preform into an optical fiber which alternates along its length between segments of different diameters, wherein the refractive index of said preform and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion at a wavelength which is greater than 1480 nm.

2. The method of claim 1, wherein the refractive index of said optical fiber preform and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion slopes at a wavelength which is greater than 1480 nm.

3. The method of claim 1, wherein the refractive index of said optical fiber preform and the diameters of said fiber are chosen to result in a fiber which has alternating regions of positive and negative dispersion over the wavelength range between about 1480 and 1625 nm.

4. The method of claim 2, wherein the refractive index of said optical fiber preform and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion over the wavelength range from about 1480 nm to about 1625 nm.

5. The method of claim 3, wherein said refractive index of said optical fiber preform and the diameters of the fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion slopes over the wavelength range of about 1480 to 1625 nm.

6. The method of claim 5, wherein said refractive index of said optical fiber preform results in said regions of negative dispersion corresponding to said regions of negative dispersion slope, and said regions of positive dispersion corresponding to said regions of positive dispersion slope.

7. The method of claim 1, wherein the said refractive index profile is chosen to result in said fiber alternating between regions of negative dispersion having negative dispersion slope, and regions of positive dispersion having positive dispersion slope.

8. The method of claim 1, wherein the method comprises drawing said fiber so that said segments of different diameters differ in magnitude of outside fiber diameter by greater than 3 microns.

9. The method of claim 1, wherein the method comprises drawign said fiber so that said segments of different diameters differ in magnitude of outside fiber diameter by greater than 10 microns.

10. The method of claim 1, wherein the refractive index of said preform is selected to result in said fiber comprising a core region surrounded by a cladding region, said core region comprised of an central core region which is updoped with respect to said cladding region, said central core region surrounded by a moat region which is downdoped with respect to said cladding region, and said moat region is surrounded by an annular ring region which is updoped with respect to said cladding region.

11. The method of claim 10, wherein the refractive index of said preform is selected to result in said central core region comprising a refractive index delta between about +.5 to 1.5 percent relative to the cladding layer.

12. The method of claim 11, wherein the refractive index of said preform is selected to result in said depressed moat core region comprising a refractive index delta in the range of -.15 to -.7 percent delta relative to the cladding

13. The method of claim 12, wherein said moat region is surrounded by an annular ring region which is updoped with respect to said cladding, and said refractive index of said preform is selected to result in said annular ring comprising a refractive index delta in the range of about .2 to .8 percent delta relative to said cladding.

14. The method of claim 12, wherein the refractive index of said preform is selected to result in said core comprising a b/a of between about 1.5 to 3.0, wherein a is the outer radius of the central core region and be is the outer radius of the moat region.

15. The method of claim 4, wherein the refractive index of said preform is selected to result in a net dispersion over the length of said fiber which is less than 1.0 ps/nm-km at 1550 and a dispersion slope of less than .03 ps/nm^2-km over the wavelength range 1480 to 1625 nm.

16. The method of claim 6, wherein the refractive index of said preform is selected to result in a net dispersion over the length of said fiber which is less than .5 ps/nm-km at 1550 and a dispersion slope of less than .01 ps/nm^2-km over the wavelength range 1480 to 1625 nm.

17. An optical fiber which comprises alternating sections of different diameter along its length, wherein the refractive index of said optical fiber and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion at a wavelength which is greater than 1480 nm.

18. The optical fiber of claim 17, wherein the refractive index of said blank and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion slopes at a wavelength which is greater than 1480 nm.

19. The optical fiber of claim 17, wherein the refractive index of said blank and the diameters of said fiber are chosen to result in a fiber which has alternating regions of positive and negative dispersion over the wavelength range between about 1480 and 1625 nm.

20. The optical fiber of claim 18, wherein the refractive index of said blank and the diameters of said fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion over the wavelength range from about 1480 nm to about 1625 nm.

21. The optical fiber of claim 20, wherein said refractive index of said blank and the diameters of the fiber are chosen to result in a fiber having alternating regions of positive and negative dispersion slopes over the wavelength range of about 1480 to 1625 nm.

22. The optical fiber of claim 21, wherein said regions of negative dispersion correspond to said regions of negative dispersion slope, and said regions of positive dispersion correspond to said regions of positive dispersion slope.

23. The optical fiber of claim 17, wherein the fiber alternates between regions of negative dispersion having negative dispersion slope, and regions of positive dispersion having positive dispersion slope.

24. The optical fiber of claim 17, wherein the different diameters differ in magnitude by greater than 3 microns.

25. The optical fiber of claim 17, wherein the different diameters differ in magnitude by greater than 10 microns.

26. The optical fiber of claim 17, wherein the fiber comprises a core region surrounded by a cladding region, said core region comprised of an central core region which is updoped with respect to said cladding region, and said central core region is surrounded by a moat region which is downdoped with respect to said cladding region.

27. The optical fiber of claim 26, wherein said central core region comprises a refractive index delta between about +.5 to 1.5 percent relative to the cladding layer.

28. The optical fiber of claim 27, wherein said depressed moat core region comprises a refractive index delta in the range of -1.5 to -.7 percent delta relative to the cladding

29. The optical fiber of claim 28, wherein said moat region is surrounded by an annular ring region which is updoped with respect to said cladding, and said annular ring comprises a refractive index delta in the range of about .2 to .8 percent delta relative to said cladding.

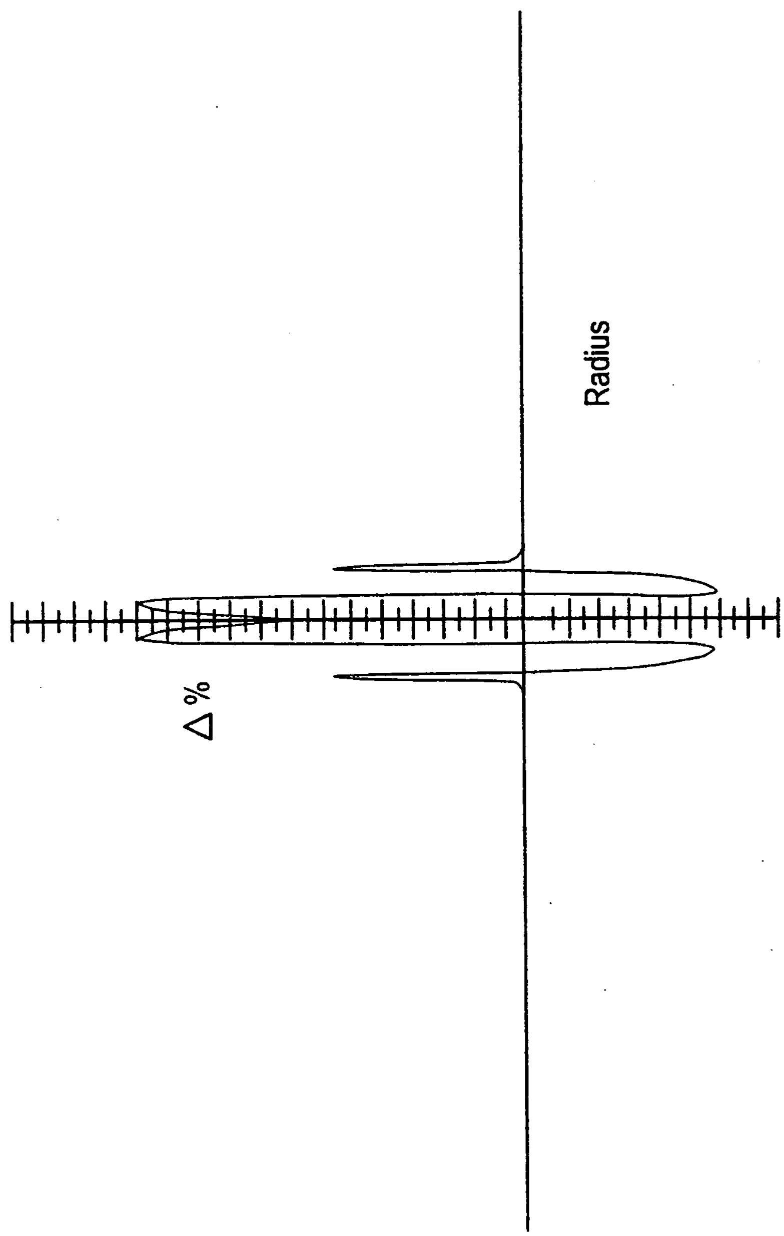
30. The optical fiber of claim 28, wherein the outer radius of the central core segment is a, the outer radius of the moat region is b, and b/a is between 1.5 and 3.0.

31. The optical fiber of claim 22, wherein the refractive index of said preform is selected to result in a net dispersion over the length of said fiber which is less

than 1.0 ps/nm-km at 1550 and a dispersion slope of less than .03 ps/nm^2-km over the wavelength range 1480 to 1625 nm.

32. The optical fiber of claim 22, wherein the refractive index of said preform is selected to result in a net dispersion over the length of said fiber which is less than .5 ps/nm-km at 1550 and a dispersion slope of less than .01 ps/nm^2-km over the wavelength range 1480 to 1625 nm.

FIG.1



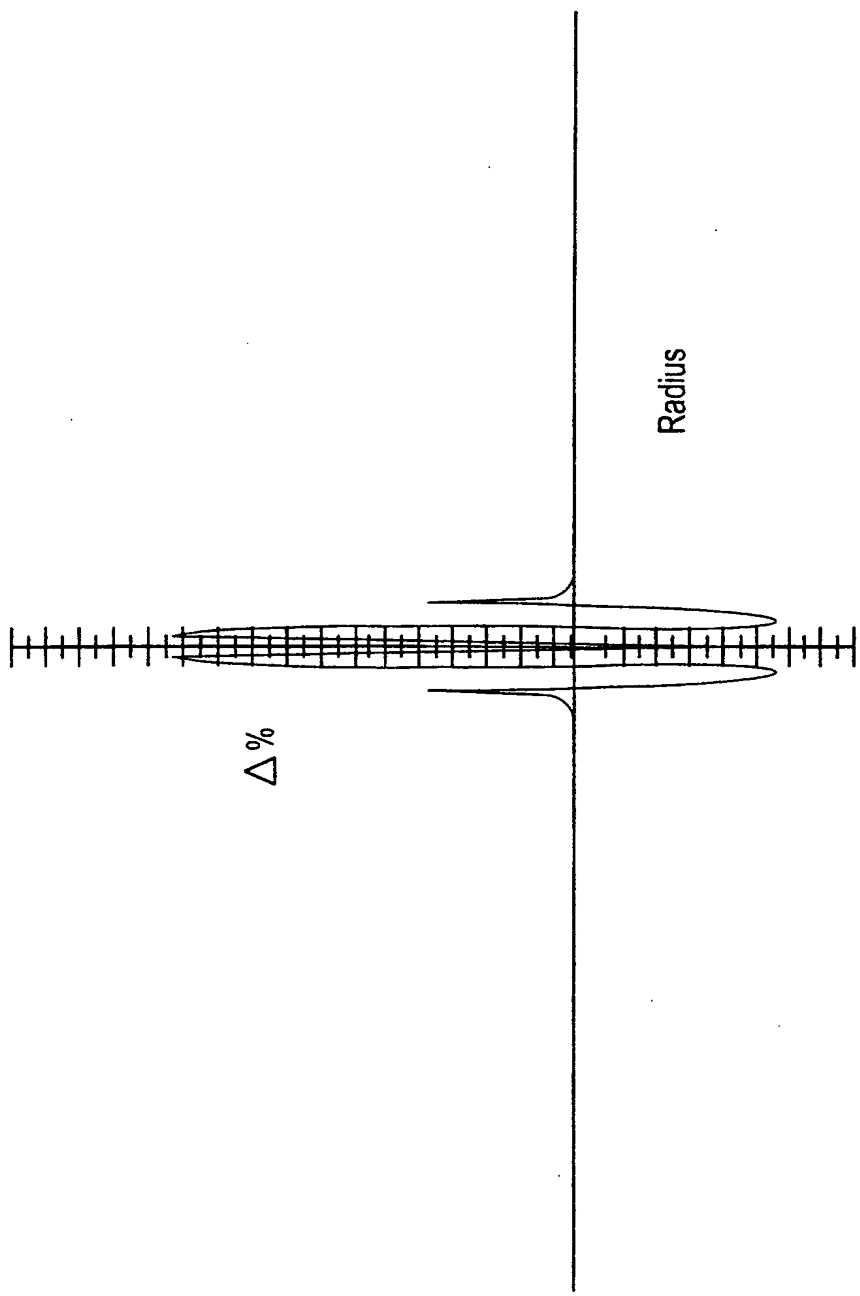


FIG.2

INTERNATIONAL SEARCH REPORT

International application No.
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A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G02B 6/02; C03B 37/02
US CL : 385/123; 65/435
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/123, 124; 65/385, 435

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS (fiber(p)((alternat? or differ?)(3A)(diameter? or core?)))

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,267,339 A (YAMAUCHI ET AL) 30 November 1993 (30/11/93), See abstract.	1-32
Y	US 5,553,185 A (ANTOS ET AL) 03 September 1996 (03/09/96), See abstract.	1-32
Y	US 5,613,028 A (ANTOS ET AL) 18 March 1997 (18/03/97), See FIG 1a & 1b.	1-32
Y, P	US 5,848,215 A (AKASAKA ET AL) 08 December 1998 (08/12/98), See claims 1 & 2.	1-32
A, P	US 5,887,105 A (BHAGAVATULA ET AL) 23 March 1999 (23/03/99), See col. 4, lines 9-27.	1-32

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search

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